

5 Patent Application of
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for
Automatic Code Generation for Integrated Circuit Design

10 RELATED APPLICATION DATA

This application is related to U.S. Patent Application No. 09/174,439, filed 10/16/1998, entitled "Data Flow Integrated Circuit Architecture," which is assigned to the assignee of the present invention, and is herein incorporated by reference.

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BACKGROUND

This invention relates to integrated circuits (ICs) and data processing systems, in particular to a method of designing integrated circuits.

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Continuing advances in semiconductor technology have made possible the integration of increasingly complex functionality on a single chip. Single large chips are now capable of performing the functions of entire multi-chip systems of a few years ago. While providing new opportunities, multi-million-gate systems-on-chip pose new challenges to the system designer. In particular, conventional design and verification methodologies are often unacceptably time-consuming for large systems-on-chip.

[illegible]

Hardware design reuse has been proposed as an approach to addressing the challenges of designing large systems. In this approach, functional blocks (also referred to as cores or intellectual property, IP) are pre-designed and tested for reuse in multiple systems. The system designer then integrates multiple such functional blocks to generate a desired system. The cores are often connected to a common communication bus, and are controlled by a central microcontroller or CPU.

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The hardware design reuse approach reduces the redundant re-designing of commonly-used cores for multiple applications. At the same time, the task of interconnecting the cores is often relatively time-consuming and error-prone. In common
30 industry practice, large amounts of hardware description language (HDL) code are written manually for interconnecting the various cores of the system. If one designer changes the interface signals of a block but does not communicate the

change to another designer responsible for the interconnection code, valuable time is wasted debugging the design.

5 In order to verify that a given HDL design performs correctly, it is common to build a behavioral (functional) model of the algorithm in a software language such as C or C++. The results of the software model are then compared against those of the HDL model. The software and HDL model must be kept consistent with each other. Changes to one model must be
10 reflected in the other. Making such changes is typically time-consuming, and increases the chance of introducing inconsistencies between the two models. The complexity of making such changes increases if large teams of engineers are involved in the design process.

Core integration and design maintenance are particularly difficult for cores having complex and/or core-specific interfaces. Core integration and design maintenance are two of the major challenges of designing large systems integrated on a single chip using the hardware design reuse approach.

SUMMARY

25 The present invention provides a computer-implemented method of designing an integrated circuit. The method comprises establishing a central specification for the circuit, wherein the central specification designates a plurality of data driven cores and a plurality of interconnections between the cores. A software language model and a hardware description language (HDL) model are established for each core. The
30 software language model implements the internal algorithm of the core, while the HDL model implements the corresponding internal logic of the core. The central specification and the software language and HDL models for the individual cores can

be manually designed by the system designer and stored in a storage medium and/or system memory.

Software language and HDL core interconnection code is automatically generated according to the central specification, to generate a software language model and an HDL model of the circuit. The software language core interconnection code interconnects the software language models of the individual cores according to the interconnections designated in the central specification. The HDL core interconnection code interconnects the HDL models of the individual cores according to the interconnections designated in the central specification.

Preferably, the HDL core interconnection code includes port declarations, port lists, data type (e.g. wire) declarations, and bus definitions. The software language core interconnection code preferably includes declarations of tokens and pipes. The pipes are objects effecting token transfer to/from the pre-designed software language models of the cores.

Test benches for the circuit and its component cores are further automatically generated, as are logic synthesis constraints for the circuit and its components.

The design method reduces the amount of code that the system designer has to write manually, as well as the amount of work needed for design maintenance and debugging. Changes in the circuit design can be made simply in the central specification. Other parts of the design are automatically updated to reflect any changes.

DESCRIPTION OF THE FIGURES

Fig. 1 shows the internal structure of an exemplary integrated circuit formed by a plurality of interconnected data-driven cores, according to the preferred embodiment of the present invention.

Fig. 2 shows one of the cores of the circuit of Fig. 1.

Fig. 3-A is a block diagram illustrating schematically the preferred structures and process flow used for implementing a method of designing an integrated circuit according to the preferred embodiment of the present invention.

Fig. 3-B is a flowchart illustrating the steps of a method of designing an integrated circuit according to the preferred embodiment of the present invention.

Fig. 4 illustrates the preferred QuArc Design Language (QDL) code characterizing the token buses connected to the core of Fig. 2.

Fig. 5 shows the preferred QDL specification for the core of Fig. 2.

Fig. 6-A illustrates exemplary Verilog-generation macros from a Verilog template for the core of Fig. 2.

Figs. 6-B-6-H show exemplary automatically-generated Verilog core interconnection code corresponding to the macros of Fig. 6-A.

Figs. 7-A illustrates exemplary C++ code from a generic core C++ template.

Fig. 7-B shows C++ code automatically generated from the template of Fig. 7-A and the QDL specification of Fig. 5.

Fig. 7-C illustrates exemplary C++ code from a C++ template for the core of Fig. 2.

Fig. 7-D shows C++ code automatically generated from the template of Fig. 7-C and the specification of Fig. 5.

Figs. 8-A and 8-B illustrate two parts of the preferred QDL specification for another core of Fig. 1.

Fig. 9-A shows exemplary Verilog-generation macros from a Verilog template for the core of Figs. 8-A-8-B.

Fig. 9-B illustrates Verilog code automatically generated from the template of Fig. 9-A and the QDL specification of Figs. 8-A-8-B.

Fig. 10-A shows C++ code automatically generated by processing the template of Fig. 7-A and the QDL specification of Figs. 8-A-8-B.

Fig. 10-B illustrates exemplary C++ code from a C++ template for the core of Figs. 8-A-8-B.

Figs. 10-C and 10-D show C++ code automatically generated by processing the template of Fig. 10-B and the QDL specification of Figs. 8-A-8-B.

Figs. 11-A and 11-B are block diagrams of two alternative test benches suitable for verifying part of the circuit of Fig. 1.

Figs. 12-A and 12-B show exemplary Synopsys DesignCompiler Tcl script code suitable for implementing synthesis constraints according to the preferred embodiment of the present invention.

DETAILED DESCRIPTION

In the following description, the statement that two signals are asserted with a predetermined synchronous relationship is understood to mean that the first signal is asserted a predetermined number of clock cycles before the second signal, or that the two signals are asserted synchronously, where the predetermined number of clock cycles is fixed for a given interface. The statement that two signals are asserted synchronously is understood to mean that both signals are asserted simultaneously with respect to a clock signal such as the rising or falling edge of a clock waveform. The statement that a token is transferred synchronously with a first signal and a second signal is understood to mean that the token

transfer occurs on the same clock cycle as the synchronous assertion of the first and second signals. A set of elements is understood to contain one or more elements. The term integrated circuit is understood to encompass both an entire circuit implemented on a chip, and a part of an integrated circuit forming a chip.

The following description illustrates embodiments of the invention by way of example and not necessarily by way of limitation.

The presently preferred embodiments can be better understood from the ensuing description of the preferred architecture for an integrated circuit, and the preferred method of designing the integrated circuit according to the present invention.

1. Data-Driven (Data Flow) Architecture

The above-incorporated U.S. Patent Application No. 09/174,439, "Data Flow Integrated Circuit Architecture," describes in detail the presently preferred architecture for an integrated circuit. In the architectural approach described in the above-referenced application, an algorithm (e.g. the MPEG decompression process) is decomposed in several component processing steps. A data-driven core (intellectual property, functional block, object) is then designed to implement each desired step. Each core is optimized to perform efficiently a given function, using a minimal number of logic gates. Once designed, a core can be re-used in different integrated circuits.

Each core has a *clock* connection for receiving global clock signals, and a *reset* connection for receiving reset signals. The cores are interconnected through dedicated standard interfaces. Each interface includes a *ready* connection for

transferring a *ready* signal, a *request* connection for transferring a *request* signal, and a data (token) connection for transferring a token. Each core processes input tokens (data) received on its input interfaces, and generates output tokens on its output interfaces. A token is transferred from one core to the other only if the sender and receiver core assert *ready* and *request* signals, respectively, with a predetermined synchronous relationship, preferably on the same clock edge (synchronously). If an output interface is connected to more than one core, a separate *ready/request* connection pair is implemented for each core connected to the output interface.

No master controller is needed to regulate the flow of data through the cores. The handshaked connections between the cores create an elastic, variable-schedule pipeline. Each sender or receiver core can stall the data stream in any clock cycle. The control of the cores essentially flows along with the transferred data--thus the terms "data driven" or "data flow" used to characterize the cores and architecture.

A core having the standard interfaces described above can be termed a *QuArc Object*. *QuArc Objects* can be classified as *Atoms* and *Molecules*. *QuArc Atoms* are *Objects* that cannot be divided into other *Objects*. *QuArc Molecules* are collections of interconnected *Atoms* and/or other *Molecules*. *Atoms* are degenerate forms of *Molecules*, leaf-level modules in the design hierarchy.

Fig. 1 shows a diagram of an exemplary integrated circuit according to the preferred embodiment of the present invention. Circuit 10 may be part of a larger system integrated on a single chip. Circuit 10 may also form essentially the entire circuit of a chip. Integrated

circuit **10** comprises a plurality of data-driven cores **12** interconnected by standard QuArc interfaces **13**. Each core **12** is of at least finite-state-machine complexity, and performs a predetermined function.

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Circuit **10** shown in Fig. **1** is an MPEG-2 video decoder core. The particular functionality of circuit **10** is shown as an example only. A methodology of the present invention can be used to design integrated circuits implementing algorithms for a variety of applications, including without limitation digital video and audio processing, data compression and decompression, and wireless and networking packet processing.

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Each core **12** of circuit **10** has a name of the form *qa_suffix* or *qm_suffix*, where the prefix *qa_* denotes an Atom and the prefix *qm_* denotes a Molecule. Integrated circuit **10** itself is a Molecule with the name *qm_m2vd*. The name of each core **12** is shown in bold within the corresponding box denoting the core, while the function of each core **12** is shown in italics. Molecule *qm_m2vd* comprises two Molecules (*qm_miq1* and *qm_idct2*), three Atoms (*qa_mvp16*, *qa_mmv*, and *qa_mmc32*), and on-chip static random access memory (SRAM) connected to Atom *qa_mmc32*. Molecule *qm_miq1* comprises Atoms *qa_miq*_a and *qa_miq*_c and on-chip SRAM modules connected to each Atom. Molecule *qm_idct2* comprises three Atoms *qa_idct08*, *qa_idctc*, and *qa_idct08*, and SRAM connected to Atom *qa_idctc*.

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Molecule *qm_m2vd* has two dedicated input interfaces, *vp_bs* and *mcr_dat*, for receiving an MPEG-2 Video bitstream and prediction data, respectively. Molecule *qm_m2vd* further has three dedicated output interfaces, *mcr_mot*, *mcw_mot*, and *mcw_dat*, for sending prediction requests, frame write requests, and frame write data, respectively. Molecule *qm_m2vd* also has plural internal interfaces (*vp_mvp*,

mvp, *iqz*, *dat*, *iq_dat*, *i_dat*, *c_dat*, *r_dat*, *o_dat*, *dct_dat*, *pat*, and *cmd*) for transferring tokens between its component Objects.

Fig. 2 illustrates in detail Atom *qa_mvp16* and its input and output interfaces *vp_bs*, *vp_mvp*. Input interface *vp_bs* includes a control bus **14a** with a pair of standard ready/request control connections for transferring control signals. The control connections include a ready connection *bs_rdy* for receiving a *ready* signal indicative of the external availability of a token for transmittal to Atom *qa_mvp16*, and a request connection *bs_req* for transmitting a *request* signal indicative of the capability of Atom *qa_mvp16* to receive a token.

Similarly, output token bus *vp_mvp* includes a control bus **16a** with a pair of standard ready/request control connections for transferring control signals. The control connections include a *ready* connection *mvp_rdy* for sending a *ready* signal indicative of the internal availability of a token for transmittal, and a *request* connection *mvp_req* for receiving a *request* signal indicative of an external capability to receive a transmitted token.

Input interface *vp_bs* further includes a token bus **14b** with a set of data connections (wires) for receiving tokens from an external source. The wires of token bus **14b** are grouped into logical units called *fields*: a one-bit field, *bs_id*, and a sixteen-bit field *bs_data*. The bit range of field *bs_data* is shown as [15:0]. The field *bs_id* transmits bistream data ID information (0 for data, 1 for flags), while the field *bs_data* transmits corresponding data/flags.

Similarly, output interface *vp_mvp* comprises a token bus **16b** with a set of data connections (wires) for sending tokens to cores *qm_miq1* and *qa_mmv* (shown in Fig. 1). Referring back to Fig. 2, token bus **16b** comprises a plurality of fields:

5 *mvp_mpeg* (parser MPEG standard, 0 = MPEG1, 1 = MPEG2),
mvp_layer (parser layer), *mvp_ext* (parser extension ID),
mvp_code (parser code), and *mvp_data* (parser data). The bit range for each field is shown in Fig. 2 after each field name.

10 Atom *qa_mvp16* also includes a *clk* connection for receiving global clock signals, and a *rst* connection for receiving reset signals. Atom *qa_mvp16* further includes internal control logic (not shown) connected to its control and data connections, for controlling the sending and receiving of tokens upon the synchronous assertion of *rdy/req* signal pairs on its input and output interfaces. The preferred internal structures and operational steps involved in token transfer are described in detail in the above-incorporated U.S. Patent Application No. No. 09/174,439, "Data Flow Integrated Circuit Architecture," and will not be described here further.

As will be apparent to the skilled artisan, each of the cores **12** illustrated in Fig. 1 is structured as exemplified above with reference to Atom *qa_mvp16*. Each core has a *req/rdy* control pair on each interface, and each token bus of the core can have one or more fields. If a core output interface is connected to more than one other core, the output interface includes a *rdy/req* control pair for each core connected to the output interface.

2. Overview of System Design Process

According to the preferred embodiment of the present invention, an integrated circuit is built by interconnecting pre-designed data-driven cores having the above-described

standard interfaces. Building the integrated circuit includes multiple steps: establishing a Hardware Description Language (HDL) description of the circuit; establishing a software language model of the circuit, for testing the circuit's functionality; establishing "test benches" for testing the HDL model of the circuit, running the test benches, and comparing the outputs of the HDL model with those of a corresponding software language model; when the HDL description is deemed satisfactory, synthesizing the HDL description into a gate-level description of the circuit, using commercially available logic synthesis tools.

In building a system from pre-designed cores according to industry practice, the system designer would ordinarily be faced with writing large amounts of code for interconnecting the various system constructs such as cores and test bench components. The system designer would need to write HDL code defining various interconnections between pre-designed HDL representations of cores; software language code specifying how tokens are transferred between pre-designed software models of cores; HDL and/or software code specifying interconnections and/or token transfer within test benches; and instructions constraining/directing the synthesis tools.

According to the preferred embodiment of the present invention, the tasks of interconnecting the cores and testing the resulting circuit are simplified by first establishing a central, high-level-language specification of the circuit, and then automatically generating the various required HDL, software language, and synthesis code from the central specification. The presently-preferred high-level language will be hereinafter termed QuArc Design Language, or QDL.

Fig. 3-A illustrates schematically the structures and steps involved in designing an integrated circuit such as circuit 10 according to the preferred embodiment of the present invention. The system designer starts with a manually-designed QDL central specification 18 for the circuit, as well as a set of HDL templates 20a and software language templates 20b for the component cores of the circuit. Each template 20a comprises HDL code defining the internal logic of a component core. Similarly, each template 20b comprises software language code defining the internal functionality (algorithm) of a component core.

An Automatic Configuration Tool (ACT) 22 automatically generates an HDL wrapper 24a and a software language wrapper 24b from QDL specification 18. Wrapper 24a comprises HDL core interconnection code interconnecting the internal logic of different component cores defined in templates 20a. Similarly, wrapper 24b comprises software language core interconnection code for transferring tokens between the internal algorithm code of templates 20b. Preferably, the automatic generation of wrappers 24a-b by the ACT is driven by macro (command) statements incorporated in templates 20a-b. An HDL model 26a of the circuit is formed by adding the code of HDL wrapper 24a to the code of HDL templates 20a. Similarly, a software model of the circuit is formed by adding the code of software language wrapper 24b to the code of software language templates 20b.

ACT 22 further generates a synthesis driver 28 from QDL specification 18. Synthesis driver 28 incorporates a set of synthesis constraints for HDL model 26a. Synthesis driver 28 is used by conventional logic synthesis tools to generate a gate-level netlist 30 from HDL model 26a. Conventional logic

synthesis tools are also used to generate a chip layout **32** for the circuit from netlist **30**.

ACT **22** generates a set of test benches **34** for the circuit from QDL specification **18**. Test benches **34** can include a test bench for the entire circuit, as well as test benches for component Atoms and Molecules of the circuit. Test benches **34** incorporate HDL and software language models for the circuit and/or component cores, as well as driver and monitor modules for driving and monitoring the HDL and software modules. Test benches **34** are used to verify that the HDL and corresponding software language models of the circuit and/or component cores produce identical results. The software and hardware results produced by each test bench **34** are preferably generated in parallel. The results of the software and hardware simulations can be compared in real time, before the entire simulations are complete.

A set of simulation results **36** are generated by running simulations of HDL model **26a**, software model **20b**, netlist **30**, and test benches **34**. Simulation results **36** can include results for the entire circuit as well as for individual components of the circuit.

Fig. **3-B** is a flow chart schematically illustrating the principal design and verification steps performed according to the preferred embodiment of the present invention. In Step 1, a QDL central specification for the circuit and a set of template files for the component Objects are established. The set of template files includes HDL and software language template files (models) for Molecules and Atoms, as well as test bench and synthesis script templates. The ACT is used to automatically generate hardware description language (HDL) and software language code for the integrated circuit from the

central specification and the template files (Steps 2 and 3). The automatically-generated code establishes the necessary control signal and token transfer connections between the different pre-defined Objects.

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Test benches for the circuit and its component Objects are also automatically generated (Step 4). Hardware and software simulations for the circuit and each of its components Objects are run, and the simulation results are evaluated (Step 5). Ideally, the results of the software and hardware simulations match for each Object and for the entire circuit. If the HDL design is satisfactory, appropriate synthesis constraints are generated and conventional logic synthesis tools are used to synthesize the design (Step 6). The design can be further tested at the netlist level. The synthesized design can then be physically implemented in silicon.

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The steps above need not be performed in the exact order shown. Moreover, the component Objects of the circuit are preferably designed and tested before the circuit is designed and tested as a whole.

The QDL description of circuit **10** preferably includes declarations of: the fields of each token bus (interface) type; the Atoms in the design, their configuration parameters, and their interfaces (input and output token buses); the Molecules in the design, their configuration parameters, their interfaces, the Objects instantiated in each molecule, and the way the Objects are interconnected. The QDL specification of each component core can be incorporated in the central specification using a command such as #include. The QDL description essentially specifies, in a compact, centralized manner, the component Objects of circuit **10** and how the Object interfaces are interconnected.

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Each part of the QDL description and its use in automatically generating hardware (HDL) and software language code will now be described in detail with reference to exemplary Objects/circuits.

3. Token Buses: QDL Specification

Fig. 4 shows preferred QDL specification code 40 for the token buses of Atom *qa_mvp16* illustrated in Fig. 2. Code 40 includes declarations of the two token buses *vp_bs* and *vp_mvp* of Atom *qa_mvp16*. For each token bus, the component fields and bit-ranges (widths) for the fields are defined. The default bit range is zero, as illustrated by the *bs_id* field. Optional comments can be included. For each field, characteristics such as *sign* (e.g. signed or unsigned) or *direction* (e.g. normal or invert) can be defined if needed. The *sign* characteristic can be useful for behavioral, software language (e.g. C++) descriptions of Atoms.

The token bus specification can be parameterized. For example, a *range* declaration can have the form *[DW-1:0]*, where *DW* is a data width parameter previously declared in the QDL specification of circuit 10. The value of the parameter *DW* can be defined by a declaration such as "var *DW* = expression."

Code 40 is maintained in a dedicated token description file, e.g. a file named "token.qdl." The token description file contains declarations of each token bus within circuit 10.

4. Atom: QDL Specification, HDL Code, Software Code

4A. Atom: QDL Specification

Fig. 5 shows preferred QDL specification code 50 for the Atom *qa_mvp16* illustrated in Fig. 2. Code 50 includes a set

of parameter declarations, illustrated in Fig. 5 by the parameters *BSN* and *BSW*. Parameter *BSN* is a bitstream number, while parameter *BSW* is the width of the bitstream number *BSN*. Code 50 also includes a set of standard input port declarations, illustrated in Fig. 5 by the declarations *clk* and *rst_*. The underscore at the end of the *rst_* signal name signifies that the signal is active low. The standard ports are present in every Object of circuit 10.

The specification further includes a set of input and output token declarations, illustrated by tokens *vp_bs* and *vp_mvp*. For each token bus, the declaration includes the bus type and an optional port name. The token bus type (e.g. *bs*, *mvp*) is defined in the token specification of Fig. 4. The token port name (e.g. *vp*) is chosen by the system designer, and may be omitted if only one bus of a given token bus type is present within circuit 10.

By default, each control bus corresponding to a given token bus includes both control connections *rdy* and *req*. If only one control connection is desired, the corresponding token declaration in the QDL specification can include, in addition to *port* and *type* declarations, a command designating the sole control connection. The command can have the form *flow_control = rdy_only* or *flow_control = req_only*. The default configuration (both *rdy* and *req*) can also be explicitly declared as *flow_control = rdy_req*.

4B. Atom: HDL Code

The token and Atom QDL specifications 40, 50 shown in Figs. 4 and 5 are used in conjunction with a template HDL (e.g. Verilog) file for Atom *qa_mvp16* to automatically generate a final HDL file for Atom *qa_mvp16*. The template file is set up by an engineer. The Automatic Configuration Tool (ACT) is

then used to process the QDL specification to add code to the template file and thus automatically generate the final HDL file for Atom *qa_mvp16*. The added code serves to establish connections between the pre-defined internal logic of the Atom and QDL-defined external bus wires.

Fig. **6-A** shows exemplary code **60a** from the preferred Verilog template file of Atom *qa_mvp16*. In addition to code **60a**, the template includes Verilog code for the internal logic of Atom *qa_mvp16*, for example the registers, adders, multipliers for a conventional MPEG-2 video parser (not shown). The internal logic code is pre-designed by the engineer by well-known methods.

Code **60a** comprises a plurality of macros (instructions), shown in bold in Fig. **6-A**. The Automatic Configuration Tool (ACT) processes the macros to add the desired interface HDL code to the templates. Code **60a** includes five macros, which instruct the ACT to generate HDL code for: a port list (QDL_PORT_LIST), a parameter list (QDL_PARAM_LIST), bus definitions (QDL_BUS_DEFS), port declarations (QDL_PORT_DECL), and port wires (QDL_PORT_WIRE). The wire declarations are examples of data type declarations. Other data type declarations can be, for example, register declarations.

Each macro declaration is enclosed between comment signs, and is thus ignored by the HDL compiler but not by the ACT. The macros replace the sections of code in which a designer would otherwise put the interface port list, port declarations, bus definitions, wire declarations, and parameter list.

Figs. **6-B** through **6-F** show Verilog exemplary code added to the template Verilog file of Atom *qa_mvp16* by processing the five macros of Fig. **6-A**, respectively. The information needed for

the processing of the macros is taken from QDL code 40, 50 shown in Figs. 4 and 5.

Fig. 6-B shows an exemplary port list 60b generated by the ACT by processing the port list macro QDL_PORT_LIST of Fig. 6-A. Port list 60b includes a listing of all ports corresponding to the fields shown in Fig. 2. To generate port list 60b, the ACT incorporates the token bus field declarations of Fig. 4 into the token declarations of Fig. 5. Declarations for the required *rdy/req* connections for each token bus are automatically generated from QDL code 50. Declarations for the required ports *clk* and *rst_* are also automatically generated.

Fig. 6-C shows an exemplary parameter list 60c generated by the ACT by processing the parameter list macro QDL_PARAM_LIST of Fig. 6-A. Parameter list 60c lists 3 parameters: the bitstream number *BSN* and the bitstream width *BSW* defined in the atom QDL specification 50 (Fig. 5), and a connection number parameter *MVP_NR*. The definition of *BSW* shown in Fig. 6-C is a boolean restatement of the $BSW = \log_2(BSN)$ definition in the QDL specification 50 of Fig. 5. The connection number *MVP_NR* is set by default to 1, but can be set at the Molecule level to be equal to the number of objects connected to the bus *MVP*, as will be apparent from the description below. The parameter *MVP_NR* is not explicitly declared in the QDL specification 50, and it is automatically generated by the ACT.

Fig. 6-D shows an exemplary set of bus definitions 60d generated by the ACT by processing the bus definition macro QDL_BUS_DEFS of Fig. 6-A. For each token field 14b, 16b shown in Fig. 3, the ACT defines parameters such as *field_MSB* (most-significant bit), *field_LSB* (least significant bit), and

field_W (width). For each token *BS* and *MVP*, a total width parameter *token_all* is further generated by summing the widths of the component fields of the token.

Fig. 6-E illustrates an exemplary set of port declarations **60e** generated by the ACT by processing the port declaration macro QDL_PORT_DECL of Fig. 6-A. The port declarations define the fields of the token buses *bs* and *mvp* as inputs or outputs, and specify bit ranges for the fields. The bit ranges incorporate the bus definition parameters shown in Fig. 6-D, as well as the parameter *MVP_NR* (the number of cores connected to the output token bus) shown in Fig. 6-C.

Fig. 6-F shows an exemplary set of port wires **60f** generated by the ACT by processing the port wire macro QDL_PORT_WIRE of Fig. 6-A. As illustrated, wires and associated bit ranges are declared for the signal outputs shown in Fig. 2.

The above-described ports and wires are connected to the pre-designed internal logic of Atom *qa_mvp16* through instantiated standard QuArc interfaces (library cells). These library cells implement the *rdy/req* token transfer protocol and associated timing constraints.

Figs. 6-G and 6-H illustrate exemplary Verilog code **60g-h** for instantiated standard QuArc input and output interfaces *ql_qi* and *ql_qo*, respectively. The two interfaces establish connections between the internal logic of Atom *qa_mvp16* and the various fields of buses *vp_bs* and *vp_mvp*. For example, input interface *ql_qi* connects its pre-defined data connection *.idata* to the input token bus *vp_bs*. Similarly, output interface *ql_qo* connects its predefined data connection *.odata* to the output token bus *vp_mvp*.

4C. Atom: Software Code

Preferably, the system designer implements an algorithmic (bit-accurate) model of circuit **10** in an object-oriented software language such as C++ or Java. Preferably, for each Atom of circuit **10**, the system designer sets up template software files. If C++ is employed, it is preferred that the designer use two templates: a header (.hh) template and a main source (.cc) template. The header template is completely generic, and is identical for all Objects. The main source template is Object-specific. The template files are then processed by the ACT to generate the final software source code for circuit **10**. In particular, the ACT generates code that sets up the communication (interfaces) to other Objects and any other required file input/output (I/O). Communication is preferably set up through C++ objects termed here "pipes." Each pipe corresponds to an Atom interface, and serves to transfer tokens to and from the pre-defined internal code implementing the Atom's algorithm.

Fig. **7-A** shows exemplary C++ code **70a** for a generic header template for an Object (Atom or Molecule). Boldface text indicates code to be modified using QDL specification information. As shown, code **70a** includes two macros, which instruct the ACT to generate C++ code for pipe declarations (QDL_FDS_PIPE_DECL) and for token declarations (QDL_TOKEN_DECL), as will be described in further detail below. The pipes are objects that transfer tokens to and from the core of interest. Code **70a** further comprises instructions including the declaration QDL_NAME, which is then replaced by the ACT with the actual name of the Object. In particular, code **70a** defines an Object class QDL_NAME, and a file descriptor (or Object connection) class QDL_NAME_FDS. The class QDL_NAME_FDS contains the pipes corresponding to the core QDL_NAME. The function sim_logic simulates the internal

logic of the core, which is typically manually generated by the designer. The function `sim_core` simulates the entire core.

5 Fig. 7-B shows C++ code **70b** generated from the generic header code **70a**. Boldface text indicates code that is changed relative to the template code **70a**. In code **70b**, the actual Object name `qa_mvp16` has replaced the generic Object name declaration `QDL_NAME`. The pipe declaration macro
 10 `QDL_FDS_PIPE_DECL` has been processed to generate declarations of two pipes, `Qpipe vp_bs_fds` and `Qpipe vp_mvp_fds`, corresponding to the token buses `vp_bs` and `vp_mvp`, respectively. The token declaration macro `QDL_TOKEN_DECL` has been processed to generate the token declarations `VP_BSToken p_vp_bs` and `VP_MVPToken p_vp_mvp`. The portions `vp_bs` and `vp_mvp` of the pipe and token names are taken from the QDL specification **50** of Atom `qa_mvp16` (Fig. 5).

Fig. 7-C shows exemplary C++ code **70c** for the main source
 20 (.cc) template for Atom `qa_mvp16`. As with code **70a**, code **70c** contains references to the core name `QDL_NAME`. Code **70c** further contains three macros, which instruct the ACT to generate C++ code for: constant initializations (`QDL_CONST_INIT`), input connections (`QDL_INPUT_CONNECTIONS`),
 25 and output connections (`QDL_OUTPUT_CONNECTIONS`). The object `pf_des` specifies all the pipes of interest for the class of Atom `qa_mvp16`.

Fig. 7-D illustrates C++ code **70d** generated from the main
 30 source code **70c** and the QDL specification **50** of Atom `qa_mvp16`, shown in Fig. 5. The actual Object name `qa_mvp16` has replaced the generic Object name declaration `QDL_NAME`. The constant initialization macro `QDL_CONST_INIT` has been processed to generate initializations of the input and output tokens

p_vp_bs and *p_vp_mvp*, respectively. The input connection macro QDL_INPUT_CONNECTION has been processed to specify a data source (the pipe *vp_bs_fds*) for the input token *p_vp_bs*. The output connection macro QDL_OUTPUT_CONNECTION has been processed to specify a sink (the pipe *vp_mvp_fds*) for the output token *p_vp_mvp*.

The discussion above has shown in detail how HDL and software code is automatically generated from the QDL specification of an exemplary Atom. Automatically-generating HDL and software code for an exemplary Molecule is described in detail below.

5. Molecule: QDL Specification, HDL Code, Software Code

The preferred methodology and syntax for automatically generating HDL and software code for a molecule will be exemplified for the Molecule *qm_miq1* shown in Fig. 1.

5A. Molecule: QDL Specification

Figs. 8-A and 8-B illustrate two parts 80a-b of the preferred QDL specification for the Molecule *qm_miq1* shown in Fig. 1. Fig. 8-A shows code 80a including parameter, port, and token declarations similar to those of Fig. 5, while Fig. 8-B illustrates molecule-specific QDL code 80b.

As illustrated by the *#include* statement in Fig. 8-A, the QDL specification of Molecule *qm_miq1* incorporates by reference the QDL specifications of the component Objects of Molecule *qm_miq1*. Code 80a further includes: declarations of parameters (*BSN*, *BSW*), required ports (*clk*, *rst_*), and input and output tokens (*vp_mvp* and *dat*, respectively). As illustrated for the token of type *dat*, a port name for a token is not required if that token is the only of a given type within circuit 10. Moreover, the token declarations can

include parameter values, as illustrated by the value 16 assigned to the data width parameter *DW* of token *dat*.

As shown in Fig. 8-B, code 80b includes instantiation commands for each of the component Atoms *qa_miq_a* and *qa_miq_c* of Molecule *qm_miq₁*. For each Object, code 80b specifies its type (*object=* in Fig. 8-B), as well as a unique instance name (*name=* in Fig. 8-B). The instance name is particularly important if two sub-Objects of the same type are instantiated within the same Molecule. Each instantiation command includes declarations of parameters (*BSN*, *BSW*), required ports, and Object connections. As illustrated, Atom *qa_miq_a* is connected to token buses *vp_mvp* and *iqz*, while Atom *qa_miq_c* is connected to token buses *iqz* and *dat*. Each of the Atoms is further connected to on-chip RAM.

Each of the instantiation commands further includes a RAM connection macro. The RAM connection macro specifies labels for its *read* and *write* connections, the size of the RAM module, and the width of the RAM bus. For atom *qa_miq_a*, the read and write connection labels are *q*, the RAM size is 2⁷ bits, and the RAM bus width is 16 bits. For atom *qa_miq_c*, the read and write connection labels are *z*, the RAM size is 2⁶ bits, and the RAM bus width is 12 bits.

The input and output token buses *vp_mvp* and *dat* are both connected to external Objects, as illustrated by the *connect* commands in Fig. 8-A. Generally, an input bus can be set to receive a constant input, for example an input selecting a certain constant function for an Object. To connect an input bus to a constant source, the *connect* command can be replaced by a command of the form *constant {type = <token_name>; port = <port_label>; value = <expression>}*, where *expression* is a Verilog constant expression identifying the input source

for the input bus. Similarly, an output bus can remain unconnected if its corresponding token is not needed elsewhere. To leave an output bus unconnected, the *connect* command is replaced by a command of the form

5 *no_connect* {type = <token_name>; port = <port_label>}.

5B. Molecule: HDL Code

The QDL specification **80a-b** illustrated in Figs. **8-A** and **8-B** is used in conjunction with a generic Molecule template to automatically generate HDL code for Molecule *qm_miq1*. Fig. **9-A** shows the preferred generic Molecule template **90a**. Template **90a** consists of the Atom template HDL code **60a** (Fig. **6-A**), with an Object instantiation macro (*QDL_INSTANCE*) replacing the Atom's manually-designed internal logic. The instantiation macro *QDL_INSTANCE* directs the ACT to instantiate the component Objects of the Molecule.

The port list, parameter list, bus definition, port declaration, and port wire macros of code **90a** are processed to generate Verilog code for Molecule *qm_miq1*. The generated Verilog code is similar to the Verilog code shown for Atom *qa_mvp16* in Figs. **6-B** through **6-F**, with the token bus *dat* replacing the token bus *vp_mvp*. The parameter *DAT_NR* defines the bit ranges for the *dat_rdy* and *dat_req* output control

25 connections.

Fig. **9-B** shows exemplary Verilog code **90b** for Molecule *qm_miq1* generated by processing the instantiation macro *QDL_INSTANCE*. Code **90b** comprises code for the two component Atoms *qa_miq_a* and *qa_miq_c* of Molecule *qm_miq1*. Code **90b** connects the internal interface wires of each atom (*.clk*, *.rst_*, *.mvp_rdy*, etc.) to the corresponding external wires (*clk*, *rst_*, *mvp_rdy*, etc.). The internal wires include standard wires (*.clk*, *.rst_*), token bus wires (*.mvp_mpeg*, *.mvp_layer*, etc.), control

wires (*.mvp_rdy*, *.mvp_req*, etc.) and RAM interface wires (*.qaddr*, *.qrde*, etc.). RAM modules are instantiated in a similar manner.

5 5C. Molecule: Software Code

The header template (.hh) code **70a** shown in Fig. 7-A can be used for both Atoms and Molecules. Fig. 10-A shows exemplary C++ code **100a** generated by processing the generic header code **70a** and the QDL specification **80a-b** of Molecule *qm_miq1*, shown in Figs. 8-A and 8-B. Automatically-added code is shown in bold.

As shown in Fig. 10-A, the molecule name *qm_miq1* replaces the generic call QDL_NAME throughout the header file. The pipe declaration macro QDL_FDS_PIPE_DECL is expanded into declarations of the pipes *vp_mvp_fds* and *dat_fds*, each corresponding to one of the buses of Molecule *qm_miq1*. The token declaration macro QDL_TOKEN_DECL is expanded into token declarations for the input and output tokens *p_vp_mvp* and *p_dat* of Molecule *qm_miq1*.

Fig. 10-B shows exemplary C++ code **100b** from the main source (.cc) template for Molecule *qm_miq1*. Code **100b** is identical to code **70c** (Fig. 7-C) for the atom main source template, except that the body of the *sim_logic* function contains an instantiation macro QDL_INSTANCE instead of the atom algorithm. As with code **70c**, code **100b** includes a constant initialization macro QDL_CONST_INIT, an input connection macro QDL_INPUT_CONNECTIONS, and an output connection macro QDL_OUTPUT_CONNECTIONS.

Fig. 10-C shows C++ code **100c** generated by the ACT by processing the instantiation macro QDL_INSTANCE of Fig. 10-B and the molecule QDL specification **80a-b** of Figs. 8-A and 8-B.

Code **100c** instantiates the component Objects *qa_miqc* and *qa_miqq* of Molecule *qm_miq1*, and connects their interfaces via Unix pipes. Code **100c** includes a first section **102** which creates the Atom *qa_miqc* and starts its simulation, and a
5 second section **104** which creates the Atom *qa_miqq* and starts its simulation.

Fig. **10-D** shows C++ code **100d** generated by the ACT by processing the QDL_CONST_INIT, QDL_INPUT_CONNECTIONS, and
10 QDL_OUTPUT_CONNECTIONS macros of code **70c**. Code **100d** is similar to the atom code **70d** shown in Fig. **7-D**, with the token buses *vp_bs* and *vp_mvp* replaced by the token buses *vp_mvp* and *dat*, respectively.

6. Test Benches

Once the designer has generated HDL and software language models for circuit **10** and its component Objects, circuit **10** and its component Objects are tested. Preferably, test benches are generated automatically by the ACT from the QDL specifications of circuit **10** and its component Objects. Test benches are built for entire circuit **10** and for component parts of circuit **10**. The test benches are preferably built from the QDL specification of the Object to be tested, from pre-designed templates of standard test bench modules, and
20 from an input source. The system designer simply specifies to the ACT the Object for which a test bench needs to be built and an input source for the Object. The needed test bench code is then generated automatically.

30 Figs. **11-A** and **11-B** show two alternative test benches (test environments) **110a**, **110b**, respectively, constructed to test the HDL model of Molecule *qm_miq1*. Test benches **110a**, **110b** are preferably implemented on a general-purpose computer such as Unix workstation.

As shown in Fig. 11-A, test bench 110a includes a test input token source 120, an HDL simulation module 130 connected to source 120, a software language model 150 of Molecule *qm_miq1*, and an HDL interconnection module 140 interconnecting HDL module 130 and software language module 150.

Input token source 120 is preferably a file containing a plurality of test input tokens representative of the data received by Molecule *qm_miq1*. HDL module 130 comprises an HDL (e.g. Verilog) model 132 of Molecule *qm_miq1*, an HDL bus driver module 134, and an HDL bus receiver module 136. Driver module 134 is connected to token source 120, for receiving test input tokens from token source 120. Driver module 134 is further connected to the Atom *qa_miq_a* of HDL model 132 through the token bus *mvp*, for transmitting test input tokens to Atom *qa_miq_a*. Receiver module 136 is connected to Atom *qa_miq_c* through the token bus *dat*, for receiving output tokens generated by HDL model 132. HDL model 132 generates the output tokens by processing the input tokens received from driver module 134. The connections between model 132 and modules 134, 136 each include a standard *rdy/req* control pair.

Interconnection module 140 comprises a software model driver module 142, an *iqz* bus monitor module 144, and a *dat* bus monitor module 146. Driver module 142 is connected to the output of driver module 134, for receiving input tokens from driver module 134. Monitor module 144 is connected to the output of the Atom *qa_miq_a* of HDL model 132, for receiving tokens transferred from Atom *qa_miq_a* over the token bus *iqz*. Monitor module 146 is connected to the Atom *qa_miq_c* of HDL model 132, for receiving tokens transferred from Atom *qa_miq_c* over the token bus *dat*. Monitor modules 144, 146 monitor the

passage of tokens over buses *iqz* and *dat*, respectively, without affecting the token passage.

Software model **150** is a software-language (e.g. C++-written executable) model of Molecule *qm_miq1*. Model **150** has an input token bus *mvp* for receiving input tokens, an output token bus *dat* for transmitting output tokens, and an internal token bus *iqz* for transferring tokens between its component Atoms *qa_miq1a* and *qa_miq1c*. The buses *mvp*, *iqz*, and *dat* are connected to driver module **142**, *iqz* monitor module **144**, and *dat* monitor module **146**, respectively. Each connection between software model **150** and interconnection module **140** is preferably implemented over a Unix pipe **152** and a Verilog Programming Language Interface (PLI) **154**.

To verify HDL model **132**, the system designer commences the execution of modules **130**, **140**, and **150**. Bus driver module **134** sequentially retrieves input tokens from input token source **120**, and transmits the input tokens to HDL model **132** and software model driver **142**. For each input token received from bus driver module **134**, HDL model **132** generates an output token which it then makes available for transmission over its *dat* bus. The output token is transmitted to bus receiver module **136** and *dat* bus monitor module **146**. HDL model **132** further generates an intermediate token, which is transmitted over bus *iqz* to Atom *qa_miq1c* of model **132** and to *iqz* bus monitor module **144**.

Software model driver **142** transmits each input token to the Atom *qa_miq1a* of software model **150**. For each input token received, software model **150** generates an output token corresponding to the bus *dat*, and an intermediate token corresponding to the bus *iqz*. The output token is transmitted

to *dat* bus monitor module **146**, while the intermediate token is transmitted to *iqz* bus monitor module **144**.

5 Bus receiver module **136** serves to verify that the standard *rdy/req* QuArc interface for the bus *dat* of HDL model **132** functions properly. Bus monitor modules **144** and **146** compare the corresponding tokens received from HDL model **132** and software model **150**. If the tokens are not identical, it is presumed that there is an error in the system design.
10 Ideally, each output and intermediate token produced by HDL model **132** is identical to a corresponding token generated by software model **150**.

For simplicity, the preceding discussion has illustrated the functioning of a test bench for a single input token and a single output token. Generally, there need not be a 1-to-1 correspondence between input and output tokens. An object under test can generate one or more output tokens from one or more input tokens. Generally, a monitor module is connected to each intermediate bus and output bus of the object to be tested, and each input bus of the object is connected to an input token source.

As shown in Fig. **11-B**, test bench **110b** includes a test input
25 token source **220**, an HDL simulation module **130**, a software language module **250** connected to token source **220**, and an HDL interconnection module **240** interconnecting HDL module **130** and software language module **250**. Token source **220** is preferably a file containing test input tokens representative of a video
30 bitstream received by Atom *qa_mvp16*. Module **250** includes software language model **150** of Molecule *qm_miq1*, a software language model **156** of Atom *qa_mvp16*, and software language models of the other Objects of the circuit under design. The output of model **156** is connected to HDL bus driver module **134**.

Interconnection module **240** comprises *iqz* bus monitor module **144**, and *dat* bus monitor module **146**. As in test bench **110a** (Fig. **11-A**), modules **144** and **146** receive input from the *iqz* and *dat* buses of model **132**, respectively. Modules **144** and **146** further receive corresponding *iqz* and *dat* tokens from software model **150**. As in test bench **110a**, all connections between software models and hardware modules are preferably implemented over Unix pipes and Verilog PLI.

During the operation of test bench **110b**, model **156** sequentially retrieves test input tokens from input token source **220**. For each test input token received, model **156** sends a corresponding output token to bus driver module **134** and Atom *qa_miqa* of model **150**. Bus driver module **134** sends each token to Atom *qa_miqa* of model **132**. As described above, bus monitor modules **144**, **146** receive the tokens corresponding to the buses *iqz* and *dat* from HDL model **132** and software model **150**. Each token generated by HDL model **132** is then compared to the corresponding token generated by software model **150**.

In both test benches **110a-b**, software model **150** and HDL model **132** run in parallel, and the simulation results are available and compared in real-time, as they are generated. Consequently, design errors can be identified without waiting for the simulation of an Object or of the entire circuit to end. The early identification of design errors allows shortening the time required for debugging, and simplifies the debugging process.

There is no need to manage a large number of input (stimulus) and output (result) files. Typically, if the software and hardware simulations were to be run independently, a large

number of input and output files need to be stored and managed. Furthermore, the automatic generation of the test benches from the QDL specification greatly reduces the time required to set up the test benches.

5

7. Synthesis Constraints

Once an HDL design has passed all desired verification and testing, the HDL design can be synthesized. The design can be synthesized using commercially-available synthesis tools, such as those marketed by Synopsys, Inc. The synthesis tools generate suitable logic for implementing the circuit from the HDL code for the circuit, a logic library, and a synthesis script which defines synthesis constraints. To facilitate a robust and efficient operation of the circuit, it is preferred that all interface signals adhere to a set of predetermined timing and other synthesis constraints. Adherence to the synthesis constraints ensures the preferred one-token-per-cycle operation of a circuit designed according to the present invention. The preferred synthesis constraints are described below.

The logic driving any output signal may use no more than a predetermined fraction (e.g. <50%, preferably <25%) of the cycle time (clock edge to data output). Furthermore, the logic receiving any input signal may use no more than a predetermined fraction (e.g. <50%, preferably <25%) of the cycle time, including the set-up time of any flip-flop. The above constraints facilitate token transfer on the same clock cycle as the assertion of a *rdy/req* signal pair.

Preferably, all tokens come directly from a register and go directly into a register. Requiring tokens to come out directly from a register allows reduced clock-to-output delays, while requiring tokens to go directly into a register

allows reduced set-up times. To implement the two above token transfer conditions, a more stringent timing constraint can be imposed for the token buses than for the control (rdy/req) buses. For example, the logic driving any token bus output can be required to use no more than a suitable predetermined fraction of the clock cycle. The fraction is chosen to be small enough to preclude the logic synthesis tools from inserting combinational logic at the Object inputs and outputs. Preferably, the fraction is set to 15% of the cycle time.

Since typically data transfer to and from RAM need not occur on the same clock cycle as the corresponding control signal(s), less stringent timing constraints can be used for RAM signals than for other buses. Preferably, all logic driving RAM output signals (read/write enable, address, write data) is allowed to use up to 75% of the cycle time.

It is preferred that all outputs have a standard capacitive load applied thereto. The standard capacitive load can be, for example, at least 5, preferably 20, times the input pin load of a standard-size inverter. The capacitive load ensures that the generated signal strength is sufficient for transmission to multiple receivers. In addition, all inputs preferably have a preset drive strength, preferably substantially equal to the drive of a standard 2-input NAND gate. The drive strength sets a limit on the signal strength required to drive the input.

The above-described constraints are preferably implemented through commands in the synthesis script used by the synthesis tools. The synthesis script is automatically generated by the ACT from a synthesis script template and the QDL specification of the circuit to be synthesized. The template includes

generic script code, while the ACT generates design-specific script code.

5 Figs. **12-A** and **12-B** show exemplary generic Synopsys DesignCompiler Tcl script code **320a-b**, respectively. Code **320a** and code **320b** can be part of the same file. Code **320a** (Fig. **12-A**) sets up symbolic names for the values of various synthesis timing parameters. For example, general interface input and output delay parameters (if_input_delay, 10 if_output_delay) are set to 75% of the cycle time minus the clock skew. Setting the input delay parameter to 75% of the clock cycle leaves 25% of the clock cycle for local buffering and register set-up, as required by the preferred constraint described above. Token delay parameters (token_input_delay, 15 token_output_delay) are set to 85% of the cycle time minus the clock skew. RAM input (read-data) and output (addr/enables/write-data) delay parameters (ram_input_delay, 20 ram_output_delay) are set to 75% and 25%, respectively, of the clock cycle time minus the clock skew. Code **320a** further defines load and drive parameters def_load, qif_load, and def-drive, for implementing the above-described capacitive load and drive strength conditions.

25 Code **320b** (Fig. **12-B**) includes script code for a generic procedure for applying timing constraints to an input token bus. Code **320b** sets delays for signals entering and leaving each core (set_input_delay, set_output_delay), capacitive loads for output ports (set_load or set_port_fanout_number), and drive strengths for input ports (set_drive or 30 set_driving_cell). Similar code to the one shown in Fig. **12-B** can be used to implement constraints for output token buses and RAM interfaces.

To apply the above-described constraints to circuit 10 (Fig. 1), the ACT generates all required script function calls from the QDL specification of circuit 10. For example, to apply the input and output token bus constraints to Atom *qa_mvp16*, the ACT automatically generates commands like *QsynSetTokenInConstraint vp_bs* and *QsynSetTokenOutConstraint vp_mvp*, where the bus names *vp_bs* and *vp_mvp* are taken from the QDL specification 50 (Fig. 5) of Atom *qa_mvp16*.

8. Discussion

The preceding discussion exemplifies the reduction in workload required to design an integrated circuit according to the preferred embodiment of the present invention, as compared to a method involving manually writing all the required HDL, software model, test bench, and synthesis constraint code. To build a circuit from pre-designed cores, the system designer writes manually only the relatively concise QDL specification of the circuit. The ACT then automatically generates extensive HDL model, software model, test bench, and synthesis constraint code.

The central QDL specification allows a reduction in the overhead required for design maintenance. Changes made to the QDL specification propagate to all relevant HDL, software, and test bench objects. Thus, changes in a design do not require extensive code writing or coordination between engineers working on different parts of the design. All relevant Objects are automatically mutually consistent. The QDL specification also serves as a centralized form of documentation for the design.

Automatically-generating synthesis constraints further reduces the time required to build an integrated circuit according to the preferred embodiment of the present invention. The

synthesis constraints make the inter-Object signal delays predictable. The inter-Object delays are kept to under one clock cycle, and thus should not slow down the operation of the circuit. Only a small number of wires, such as the wires carrying the clock signal *clk*, are routed globally. Predicting wire delays is a problem of particular importance for large systems-on-chip implemented using high-density manufacturing processes (0.25 μm and below).

A skilled artisan can readily produce an Automatic Configuration Tool of the present invention by supplying the above-described syntax to a publicly-available compiler such as Yet Another Compiler Compiler (YACC). The compiler can be readily used to generate a suitable Automatic Configuration Tool from the above-described syntax and methodology.

The present invention further provides computer systems programmed to perform a method of the present invention, computer-readable media encoding instructions to perform a method of the present invention, as well as integrated circuits and circuit representations designed according to a method of the present invention. Suitable computer-readable media include, without limitation, magnetic disks, hard drives, CDs, DVDs, Flash ROM, non-volatile ROM, and RAM.

Integrated circuit representations include, without limitation, software language, HDL, netlist, and logic layout representations of the circuit.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. While the preceding discussion has focused on an exemplary integrated circuit, the skilled artisan will appreciate that the described systems and methods apply to other integrated circuits, as well as to integrated

circuits forming parts of the circuit illustrated above. The methodology described above can be used for designing cores for a variety of applications, including digital signal processing (DSP) modules, discrete cosine or inverse cosine transform (DCT, IDCT) modules, arithmetic logic units (ALU), central processing units (CPUs), bit stream parsers, and memory controllers. The ready and request signals may be multi-bit signals. Automatically-generated code can include declarations of data types other than wires--e.g. registers. While the preceding discussion illustrates the invention with reference to a Verilog/C++/Unix implementation, the invention is not limited to the particular languages or environments used as examples. The Hardware Description Language employed can be Verilog, VHDL, or any other suitable hardware description language. The software language used can be C++, Java, C or any other suitable software language. A method of automatically generating code for interconnecting cores according to the present invention need not be limited to the described preferred architecture and interface protocol. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

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